

Evidence for the tensor meson exchange in the kaon photoproduction

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The contribution of the tensor meson $K_2^*(1430)$ exchange in the process $\gamma p \rightarrow K^+ \Lambda(\Sigma^0)$ is investigated within the Regge framework. Inclusion of the K_2^* exchange in the $K(494) + K^*(892)$ exchanges with the coupling constants chosen from the SU(3) symmetry leads to a better description of the production mechanism without referring to any fitting procedure. This shows the significance of the role of the tensor meson exchange to have the Regge theory basically free of parameters with the SU(3) symmetry a good approximation for the meson-baryon couplings.

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I. INTRODUCTION

It is believed that the Regge pole model could be an effective theory for high-energy hadron reactions induced by electromagnetic and mesonic probes [1, 2]. The Regge models formulated in the s -channel helicity amplitude (SCHA) [3] are favorable to the analysis of photoproduction of pseudoscalar meson since they share essentially the same production amplitude with that of the effective Lagrangian approach except for the simple *reggeization* of the t -channel meson poles [4, 5]. It is, therefore, advantageous to work with the Regge poles in the SCHA in that one exploits the effective Lagrangians to estimate the coupling constants of the exchanged meson from the decay width or from the symmetry consideration. The application of these models to physical processes is, however, limited by the large ambiguity in the coupling of meson trajectory due to the fitting of the experimental data with few meson exchanges. Within the framework of the $K + K^*$ Regge poles for kaon photoproduction, to be specific, the coupling constants of the K^* to baryons were given too large as compared to those either from the SU(3) symmetry prediction [6] or from other independent process such as the Nijmegen soft core potential for the NN interaction [7]. This large discrepancy, as shown in Table II below, demonstrates that the $K + K^*$ exchanges in current models are not enough to describe the process up to $-t \approx 2 \text{ GeV}^2$.

In this work we study the processes $\gamma p \rightarrow K^+ \Lambda$ and $\gamma p \rightarrow K^+ \Sigma^0$ at forward angles within the Regge framework and discuss the possibility of the model prediction without fit parameters for the meson-baryon couplings. From our previous analysis of the pion photoproduction [8], we recall, the inclusion of the tensor meson $a_2(1320)$ exchange in the $\pi(140) + \rho(770)$ Regge poles led us to choose a rather moderate value for the ρ -meson coupling

constants for the better description of the experimental data. (See the values compared in Table II below.) It is, then, natural to extend the model of $K + K^*$ exchanges to obtain the parameter-free prediction for the production mechanism by introducing the tensor meson K_2^* .

II. TENSOR MESON EXCHANGE AT FORWARD ANGLES

In the photoproduction amplitude for $\gamma(k) + p(p) \rightarrow K^+(q) + \Lambda(p')$,

$$\mathcal{M} = \mathcal{M}_K + \mathcal{M}_{K^*} + \mathcal{M}_{K_2^*}, \quad (1)$$

where the amplitudes relevant to the K and K^* Regge-pole exchanges are given in Refs. [5, 8], the exchange of the K_2^* Regge pole in the t -channel is written as [8–10]

$$\begin{aligned} \mathcal{M}_{K_2^*} = & \bar{u}'(p') \varepsilon_{\alpha\beta\mu\nu} \epsilon^\mu k^\nu q^\alpha q_\rho \Pi^{\beta\rho;\lambda\sigma}(q-k) \\ & \times \left[G_{K_2^*}^{(1)} (\gamma_\lambda P_\sigma + \gamma_\sigma P_\lambda) + G_{K_2^*}^{(2)} P_\lambda P_\sigma \right] \mathcal{P}^{K_2^*}(s, t) u(p) \not{p} / 2 \end{aligned}$$

with the coupling constants $G_{K_2^*}^{(1)} = \frac{2g_{\gamma K K_2^*}}{m_0^2} \frac{2g_{K_2^* N Y}^{(1)}}{M}$, $G_{K_2^*}^{(2)} = -\frac{2g_{\gamma K K_2^*}}{m_0^2} \frac{4g_{K_2^* N Y}^{(2)}}{M^2}$, and the momentum $P = \frac{1}{2}(p + p')$. The mass parameter $m_0 = 1 \text{ GeV}$ is taken for the dimensionless decay constant and M is the nucleon mass. The quantity $\Pi_{\mu\nu;\rho\sigma}(q-k) = \frac{1}{2}(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho}) - \frac{1}{3}\eta_{\mu\nu}\eta_{\rho\sigma}$ with $\eta_{\mu\nu} = -g^{\mu\nu} + (q-k)^\mu(q-k)^\nu/m_{K_2^*}^2$ is the polarization tensor of the K_2^* meson.

According to the duality expressed as the finite energy sum rule between the s -channel resonances and the t -channel Regge poles [11],

$$\int_{s_0}^{\bar{s}} ds s^n \text{Im } \mathcal{A}_{res}(s, t) = \sum_{j=K^*, K_2^*, \dots} \gamma_j(t) \frac{\bar{s}^{\alpha_j+n+1}}{\alpha_j+n+1}, \quad (3)$$

that the imaginary part of the resonance amplitude does not vanish by the optical theorem in the left hand side

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of Eq.(3) is in effect equivalent to imply $\gamma_{K^*} \neq \gamma_{K_2^*}, \dots$, in the right hand side, i.e., the violation of the exchange degeneracy (EXD) by the different residues between the K^* and K_2^* in the leading K^* trajectory [1, 2, 8]. This proves that the weak EXD of the pair $K^*-K_2^*$ is a good approximation, and hence, both the two contribute independently with the different residues (different coupling vertices in the present scheme), but share the same phase of the signature factor with each other. Thus, we use the K_2^* Regge pole of the spin-2

$$\mathcal{P}^{K_2^*}(s, t) = \frac{\pi \alpha'_{K_2^*}}{\Gamma(\alpha_{K_2^*}(t) - 1) \sin \pi \alpha_{K_2^*}(t)} \left(\frac{s}{s_0} \right)^{\alpha_{K_2^*}(t) - 2} \quad (4)$$

with the rotating phase for the nonzero imaginary part of the amplitude. Here the trajectory

$$\alpha_{K_2^*}(t) = 0.83(t - m_{K_2^*}^2) + 2 \quad (5)$$

is taken for the K_2^* with the slope the same as that of the K^* [5] and the scale factor s_0 is chosen as 1 GeV².

Avoiding fit parameters for the coupling constants of all exchanged mesons considered here we use the SU(3) relations to determine their values. We begin with the estimate of the K^*NY coupling, while the relatively well-established coupling constant g_{KNY} and radiative decay constant $g_{\gamma K \pm K^*} = 0.254$ are taken the same as those in Ref. [5] for comparison. We estimate the coupling constants of the vector meson $g_{K^*NY}^{v(t)}$ by using the SU(3) relations in which case $g_{\rho NN}^v = 2.6$ is taken from the universality of ρ meson coupling with the ratio $\alpha^v = 1$. For the tensor coupling of the ρ meson, $g_{\rho NN}^t$, we use $\kappa_\rho = 6.2$ with the ratio $\alpha^t = 0.4$ from the SU(6) quark model prediction [6].

The radiative decay, $K_2^* \rightarrow \gamma K$, is empirically known and the width reported in the Particle Data Group is, $\Gamma_{K_2^* \rightarrow K\gamma} = 0.24 \pm 0.05$ MeV. The decay width corresponding to the $K_2^*K\gamma$ vertex in Eq.(2) is given by [9]

$$\Gamma_{K_2^* \rightarrow K\gamma} = \frac{1}{10\pi} \left(\frac{g_{\gamma K K_2^*}}{m_0^2} \right)^2 \left(\frac{m_{K_2^*}^2 - m_K^2}{2m_{K_2^*}} \right)^5, \quad (6)$$

from which $g_{\gamma K K_2^*} = 0.276$ is obtained. Since there are no informations currently available for the K_2^*NY couplings except for those a_2NN and $f_2(1270)NN$, we resume the SU(3) symmetry for the tensor meson nonet coupling to baryons where the K_2^*NY coupling constants are given by

$$\begin{aligned} g_{K_2^*N\Lambda}^{(1,2)} &= -\frac{1}{\sqrt{3}}(1 + 2\alpha_{(1,2)})g_{a_2NN}^{(1,2)}, \\ g_{K_2^*N\Sigma}^{(1,2)} &= (1 - 2\alpha_{(1,2)})g_{a_2NN}^{(1,2)}, \end{aligned} \quad (7)$$

and estimate the K_2^*NY coupling constants from the knowledge of the a_2NN couplings in existing estimates. In order for the above SU(3) predictions to be reliable, it is, therefore, of importance to choose the a_2NN coupling constants on the firm ground as well as the ratio

TABLE I: SU(3) predictions for the coupling constants of the a_2NN , and K_2^*NY from the given f_2NN coupling constant.

	A	B	C	$(\frac{F}{D})_{\text{exp}} = -1.8 \pm 0.2$
$g_{f_2NN}^{(1)}$	3.38 ^a	5.26 ^b	6.45 ^c	
$g_{a_2NN}^{(1)}$	0.6	0.94	1.15	$\alpha_{(1)} = 2.67, \frac{F}{D} = -1.6$
$g_{K_2^*p\Lambda}^{(1)}$	-2.20	-3.44	-4.21	
$g_{K_2^*p\Sigma^0}^{(1)}$	-2.60	-4.08	-4.99	
$g_{a_2NN}^{(1)}$	0.73	1.14	1.4	$\alpha_{(1)} = 2.25, \frac{F}{D} = -1.8$
$g_{K_2^*p\Lambda}^{(1)}$	-2.32	-3.62	-4.45	
$g_{K_2^*p\Sigma^0}^{(1)}$	-2.56	-3.99	-4.9	
$g_{a_2NN}^{(1)}$	0.84	1.3	1.6	$\alpha_{(1)} = 2.0, \frac{F}{D} = -2.0$
$g_{K_2^*p\Lambda}^{(1)}$	-2.42	-3.75	-4.62	
$g_{K_2^*p\Sigma^0}^{(1)}$	-2.52	-3.9	-4.8	

F/D . For verification we will check the consistency of the chosen a_2NN coupling constants by using the SU(3) relation

$$g_{f_2NN}^{(1,2)} = \frac{1}{\sqrt{3}}(4\alpha_{(1,2)} - 1)g_{a_2NN}^{(1,2)}, \quad (8)$$

with the ratio and the f_2NN coupling constants which were given in more detail in the literature [12–15].

Based on the dispersion relation and on the tensor meson dominance (TMD) [12] the f_2NN coupling constants were investigated in the analysis of the backward πN scattering [13] and the $\pi\pi \rightarrow N\bar{N}$ partial-wave amplitudes [14, 15]. In these analyses we first note that $g_{f_2NN}^{(2)} \approx 0$ was obtained in common and we adopt this in Eq. (8) together with $g_{a_2NN}^{(2)} \approx 0$ in accordance with our previous result [8]. Therefore, it is reasonable to assume that $g_{K_2^*NY}^{(2)}$ is small enough to be neglected in Eq.

(7). We now focus on the estimate of $g_{f_2NN}^{(1)}$ coupling constants from these analyses to summarize the results in the first row of Table I. (In the convention of Refs. [12, 13, 15–17], $G_{f_2NN}^{(1,2)} = M\gamma_{f_2NN}^{(1,2)} = 4g_{f_2NN}^{(1,2)}$ in Eq. (2) and $G_{f_2\pi\pi} = 2m_{f_2}\gamma_{f_2\pi\pi} = 4g_{f_2\pi\pi}$ in Eq. (9) below.) The value with the superscript a in the column A is obtained from the quantity $\gamma_{f_2\pi\pi}\gamma_{f_2NN}^{(1)}/4\pi = 10.4$ GeV⁻² which was extracted from the πN scattering [13]. In the column B the value with the b is from $g_{f_2NN}^{(1)2}/4\pi = 2.2 \pm 0.9$ which was obtained in the dispersion analysis of the $\pi\pi \rightarrow N\bar{N}$ [14]. The value with the c in the last column is from $G_{f_2NN}^{(1)2}/4\pi = 53 \pm 10$ using the Regge model for the backward πN scattering [15], which also agrees with that obtained from other independent processes [16, 17]. In each column in Table I we display the SU(3) predictions from Eqs. (7) and (8) for the $g_{a_2NN}^{(1)}$ and $g_{K_2^*NY}^{(1)}$ with the ratio $F/D = -1.8 \pm 0.2$, which was determined to agree with the Regge-pole fit to the high energy experiments based on the SU(3) symmetry for the residues of the tensor meson nonet coupling to baryons [18, 19]. On the other

TABLE II: Meson-baryon coupling constants for the exchanged mesons in the $\gamma p \rightarrow \pi^+ n$ [8] and $\gamma p \rightarrow K^+ \Lambda(\Sigma^0)$ processes. The models LMR and GLV refer to Refs. [4, 5], respectively. An overall factor $\lambda = 2.18$ is taken for the absorption correction in the LMR model.

	NSC97a	LMR	GLV	Present work
$g_{\pi NN}/\sqrt{4\pi}$	3.71	3.82	3.81	3.81
$g_{\rho NN}^v$	2.97	2.8	3.4	2.6
$g_{\rho NN}^t$	12.52	40.88	20.74	16.12
$g_{a_2 NN}^{(1)}(g_{a_2 NN}^{(2)})$		-	-	1.4 (0)
$g_{K^* p \Lambda}/\sqrt{4\pi}$	-3.82	-3.87	-3.26	-3.26
$g_{K^* p \Sigma^0}/\sqrt{4\pi}$	1.16	0.76	1.26	1.26
$g_{K^* p \Lambda}^v$	-4.26	-7.29 λ	-23	-4.5
$g_{K^* p \Lambda}^t$	-11.31	-31.72 λ	57.5	-16.7
$g_{K^* p \Sigma^0}^v$	-2.46	-7.02 λ	-25	-2.6
$g_{K^* p \Sigma^0}^t$	1.15	26.82 λ	25	3.2
$g_{K_2^* p \Lambda}^{(1)}(g_{K_2^* p \Lambda}^{(2)})$		-	-	-4.45 (0)
$g_{K_2^* p \Sigma^0}^{(1)}(g_{K_2^* p \Sigma^0}^{(2)})$		-	-	-4.9 (0)

hand, we find that, among these values, the choices of $g_{f_2 NN}^{(1)} = 6.45$ and $g_{a_2 NN}^{(1)} = 1.4$ or 1.6 in the column C with the ratio $\alpha_{(1)} = 2.0$ or 2.25 are in fair agreement with $G_{a_2 NN}^{(1)2}/4\pi \approx 3$ and $|G_{a_2 NN}^{(1)}| \approx 6$ obtained from the analyses of pion photoproduction [16] and the Compton scattering [17], respectively. Thus, we favor to choose the SU(3) value $g_{a_2 NN}^{(1)} = 1.4$ as a median value together with $g_{f_2 NN}^{(1)} = 6.45$ for the estimate of the $g_{K_2^* NY}^{(1)}$ in Eq.(7).

We present in Table II the meson-baryon coupling constants of the exchanged mesons in the Regge models for the pion and kaon photoproduction. The corresponding values from Nijmegen soft core potential (NSC97a) is listed for comparison [7]. The pseudoscalar meson coupling constants in the NSC97a are deduced by using the proportional expressions of the given pseudovector ones in Ref. [20]. Note that the $K^* NY$ coupling constants determined from the SU(3) relations in the present work are the same order of the magnitude with those obtained from the NSC97a. The tensor meson couplings are obtained from SU(3) relations with $\alpha_{(1)} = 2.25$.

Before closing this section let us comment on the TMD in relation with the determination of the $f_2 NN$ coupling constants [8, 12]. The TMD with the f_2 -pole dominance in the πN scattering process leads to the following identity,

$$\frac{2}{M}(g_{f_2 NN}^{(1)} + g_{f_2 NN}^{(2)}) = \frac{g_{f_2 \pi \pi}}{m_{f_2}} \quad (9)$$

which estimates $g_{f_2 NN}^{(1)} = 2.13$ and $g_{f_2 NN}^{(2)} = 0$ with the known coupling constant $g_{f_2 \pi \pi} = 5.76$. The coupling constant $g_{f_2 NN}^{(1)}$ predicted by the TMD is small and inconsistent with those discussed above. Since the validity of the TMD in such a simple f_2 -pole description is questionable and needs further test [21, 22], we disregard the TMD prediction in this work, though a viable hypothesis analogous to the VMD.

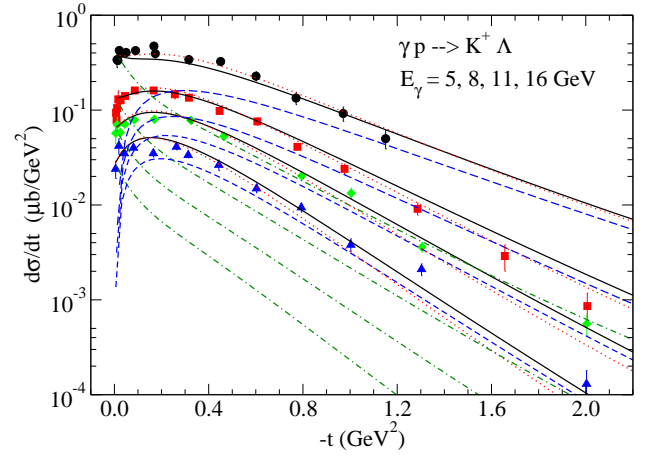


FIG. 1: (Color online) Differential cross sections $\frac{d\sigma}{dt}$ for $\gamma p \rightarrow K^+ \Lambda$ at photon energies $E_\gamma = 5, 8, 11, 16$ GeV, respectively. Solid lines (black) result from the gauge invariant $K + K^* + K_2^*$ exchanges in the present model. Dash-dotted lines (green) represent the $K + K^*$ exchanges in the present model. Dashed ones (blue) denote the K_2^* contributions. Dotted lines (red) are from the GLV model. Data are taken from Ref.[23].

III. RESULTS AND DISCUSSION

Figures 1 and 2 show the differential cross sections for $\gamma p \rightarrow K^+ \Lambda$ and $\gamma p \rightarrow K^+ \Sigma^0$ at photon energies $E_\gamma = 5, 8, 11$, and 16 GeV, respectively. It is clear that the $K + K^*$ exchanges with the SU(3) coupling constants (the green dash-dotted line) can hardly reproduce the cross section at any photon energy but the K_2^* exchange replaces the role that has been attributed to the K^* in Refs. [4, 5], instead. This feature of the production mechanism should be different from that of the $K + K^*$ exchanges (the red dotted lines) in the GLV model, even if it yields the cross sections comparable to the solid ones with very large K^* coupling constants as shown in Table II. This tendency continues to the $\gamma p \rightarrow K^+ \Sigma^0$ case, though the cross section in Fig. 2 is in less agreement with data at the photon energy $E_\gamma = 5$ GeV due to the small couplings of $KN\Sigma$ and $K^*N\Sigma$. In conclusion, the features of the production mechanism in the present work result from the $K + K_2^*$ exchanges, but not from those of the $K + K^*$ as described in previous studies. In both processes the K_2^* interferes constructively with the sum total of $K + K^*$ to reproduce the solid line. To a change of the K_2^* coupling constant within the uncertainty of the F/D ratio, the cross section shows sensitivity to some degree. But in any cases we find that the K_2^* plays the key role to reproduce the whole structure of the cross section.

The recoil polarization P is analyzed in Fig. 3. The negative value of the P observed in the experiment indicates a spin-down of the recoiled Λ , supporting our SU(3) predictions for the negative signs of the $K_2^* NY$ and $K^* NY$ couplings as well. Note that the inclusion of the K_2^* makes improved the model prediction from that

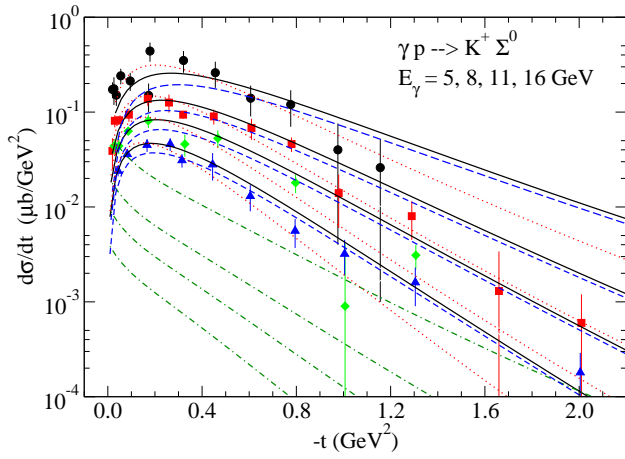


FIG. 2: (Color online) Differential cross sections $\frac{d\sigma}{dt}$ for $\gamma p \rightarrow K^+ \Sigma^0$ at photon energies $E_\gamma = 5, 8, 11, 16$ GeV, respectively. Notations are the same with Fig. 1. Data are taken from Ref.

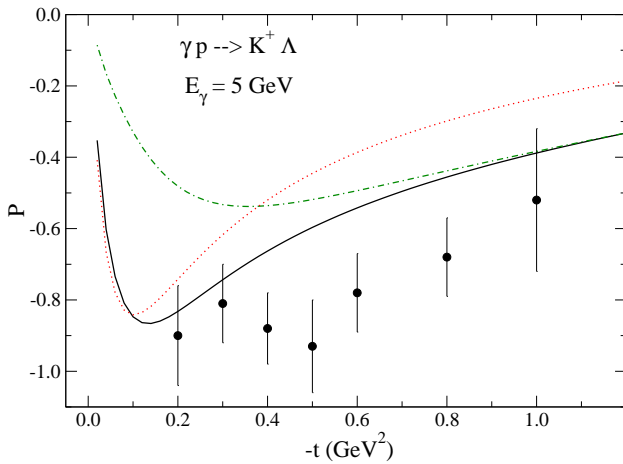


FIG. 3: (Color online) Recoil polarization asymmetry for $\gamma p \rightarrow K^+ \Lambda$ at $E_\gamma = 5$ GeV. Notations are the same with Fig. 1. Data are taken from Ref. [25].

of $K + K^*$ to the experimental data closely. For the photon polarization in the $\gamma p \rightarrow K^+ \Lambda$, we obtain exactly the same result at $E_\gamma = 16$ GeV as presented in Ref. [5] which shows the rapid approach to unity by the dominance of the natural parity exchanges, $K^* + K_2^*$ over the unnatural parity K .

Finally, we should remark upon the effect of the K_2^* exchange on the lower energy region. Figure 4 shows the total cross section measured at the SAPHIR/ELSA [26, 27] and the CLAS/JLab experiments in the reso-

nance region [28]. The size of the cross section largely depends on the magnitude of the leading coupling constant $g_{KN\Lambda}$, as can be expected from the significance of the nucleon Born term in this region. The destructive interference between the K and K^* exchange leads to a sizable reduction of the total cross section, while the K_2^* gives the additive contribution to the $K + K^*$, and we obtain a good agreement with the experimental data by using the same $g_{KN\Lambda}$ as that of the GLV model. It is understood that the overestimation of the cross section (the red dotted line) by the latter model is, therefore, another evidence for the inadequacy of such a large K^* coupling constants as fitted to the high-energy data.

In this letter, with such compelling evidences as shown, we have clarified two points that have been obscure as concerns the Regge approach to kaon photoproduction based on the s -channel helicity amplitude [4, 5, 29]; one is our current misunderstanding of the large K^* contribution due to the fitting procedure without the K_2^* . The other is the possibility of the Regge theory to be basically free of parameters with the SU(3) symmetry quite a good approximation for the meson-baryon couplings by considering the tensor meson K_2^* .

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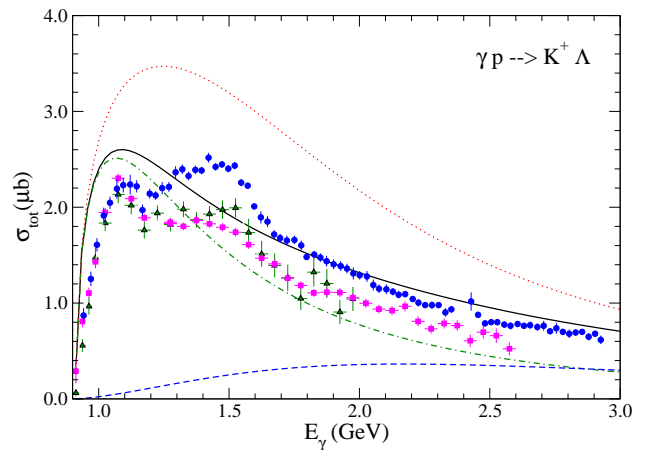


FIG. 4: (Color online) Total cross section for $\gamma p \rightarrow K^+ \Lambda$ up to $E_\gamma = 3$ GeV. Notations are the same with Fig. 1. Data are taken from [26–28].

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